A Comparison between Ranolazine and CVT-4325, a Novel Inhibitor of Fatty Acid Oxidation, on Cardiac Metabolism and Left Ventricular Function in Rat Isolated Perfused Heart during Ischemia and Reperfusion

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ABSTRACT

Inhibition of fatty acid oxidation has been reported to be cardioprotective against myocardial ischemic injury; however, recent studies have questioned whether the cardioprotection associated with putative fatty acid oxidation inhibitors, such as ranolazine and trimetazidine, are due to changes in substrate oxidation. Therefore, the goals of this study were to compare the effects of ranolazine with a new fatty acid oxidation inhibitor, CVT-4325 \((\text{R})-1-(2\text{-methylbenzo}[d]thiazol-5-yloxy)-3-(4-((5-(4-(trifluoromethyl)phenyl)-1,2,4-oxadiazol-3-yl)methyl)piperazin-1-yl)propan-2-ol\), on carbohydrate and fatty acid oxidation and on left ventricular (LV) function in the response to ischemia/reperfusion in rat isolated perfused hearts. Metabolic fluxes were determined in hearts perfused in an isovolumic Langendorff mode using \(^{13}\text{C}\) nuclear magnetic resonance isotopomer analysis or in isolated working hearts using \([14\text{C}]\)glucose and \([3\text{H}]\)palmitate, with and without 10 \(\mu\text{M}\) ranolazine or 3 \(\mu\text{M}\) CVT-4325. Isovolumic perfused hearts were also subjected to 30 min of low-flow ischemia (0.3 ml/min) and 60 min of reperfusion, and working hearts were subjected to 15 min of zero-flow ischemia and 60 min of reperfusion. Regardless of the experimental protocol, ranolazine had no effect on carbohydrate or fatty acid oxidation, whereas CVT-4325 significantly reduced fatty acid oxidation up to 7-fold with a concomitant increase in carbohydrate oxidation. At these same concentrations, although ranolazine significantly improved LV functional recovery following ischemia/reperfusion, CVT-4325 had no significant protective effect. These results demonstrate that at pharmacologically relevant concentrations, ischemic protection by ranolazine was not mediated by inhibition of fatty acid oxidation and conversely that inhibition of fatty acid oxidation with CVT-4325 was not associated with improved LV functional recovery.

Despite significant advances in treatment (Theroux et al., 2000), coronary heart disease still accounts for one in five deaths in the United States. During the past 30 years, numerous experimental interventions have been reported to limit ischemic injury in experimental animals; however, with the exception of timely reperfusion, none has translated into routine clinical practice (Bolli et al., 2004). Glucose-insulin-potassium therapy has yielded encouraging results (Fath-Ordoubadi and Beatt, 1997; Diaz et al., 1998; van der Horst et al., 2003); however, despite its potential, glucose-insulin-potassium therapy has not been widely accepted. This is due, at least in part, to the complexity of the treatment regimen and the limitations associated with infusion of large volumes of fluid into patients with compromised cardiac function (van der Horst et al., 2003). An alternative approach that potentially avoids these complications is direct pharmacological modulation of cardiac fatty acid and carbohydrate metabolism (Stanley et al., 1997b). This has been the focus of many studies of putative fatty acid oxidation inhibitors, such as trimetazidine and ranolazine, for the treatment of ischemic disease (Fragasso et al., 2002; Chaitman et al., 2004a).

However, despite the considerable interest in metabolic

ABBREVIATIONS: LV, left ventricular; NMR, nuclear magnetic resonance; DMSO, dimethyl sulfoxide; EDP, end diastolic pressure; LFI, low-flow ischemia; TCA, tricarboxylic acid; LVDP, left ventricular developed pressure; ANOVA, analysis of variance; MVO\(_2\), oxygen consumption; RPP, rate-pressure product; RAN, ranolazine; CVT-4325, \((\text{R})-1-(2\text{-methylbenzo}[d]thiazol-5-yloxy)-3-(4-((5-(4-(trifluoromethyl)phenyl)-1,2,4-oxadiazol-3-yl)methyl)piperazin-1-yl)propan-2-ol.\)
modulation as a therapy for myocardial ischemia, there is little consensus regarding the mechanism(s) underlying its possible cardioprotective effects. Recently, we reported that, although increasing glucose and insulin levels improved left ventricular (LV) functional recovery following ischemia, this was not associated with a significant effect on glucose oxidation (Wang et al., 2005). In contrast, in the same study, stimulation of glucose oxidation with dichloroacetate did not improve LV functional recovery following ischemia. Furthermore, although there is substantial evidence that trimetazidine and ranolazine are protective against the deleterious effects of myocardial ischemia in experimental and clinical settings (Gralinski et al., 1994; Zacharowski et al., 2001; MacInnes et al., 2003; Belardinelli et al., 2006), the data supporting their effect to inhibit fatty acid oxidation are less clear. For example, Saeedi et al. (2005) demonstrated that although trimetazidine significantly improved LV functional recovery in hypertrophied hearts, it had no effect on either glucose or palmitate oxidation. Likewise, MacInnes et al. (2003) reported that trimetazidine did not inhibit β-oxidation in cardiomyocytes, and although ranolazine did inhibit fatty acid oxidation, this was only by 12% at a concentration of 100 μM, which exceeds the human therapeutically range by 10-fold. More recent reports suggest that the protective effect of ranolazine could be mediated via alterations in Ca2+ homeostasis (Fraser et al., 2005, 2006; Belardinelli et al., 2006), thus providing an alternative mechanism of action.

The controversy regarding both the mechanism of action of ranolazine as well as the putative beneficial effects of inhibiting fatty acid oxidation may be attributed to several factors, including the use of different perfused heart models, such as isotopemic Langendorff perfused heart and ejection “working” heart preparations; different types of ischemia, such as zero- versus low-flow ischemia; different exogenous fatty acid concentrations; and different methods for measuring substrate utilization. Furthermore, the effects of putative “partial fatty acid oxidation inhibitors” such as ranolazine have not been directly compared with the effects of more potent fatty acid oxidation inhibitors. Recently, we have developed a new potent fatty acid oxidation inhibitor, CVT-4325, which has an IC50 of 0.9 μM for inhibiting fatty acid oxidation in the presence of 1.2 mM palmitate (Fraser et al., 2003). Therefore, the goal of this study was to directly compare the metabolic effects of ranolazine with CVT-4325 in two different heart perfusion models and measure substrate utilization using both [13C]glutamate NMR isotopomer analysis and radioisotope techniques.

We found that, regardless of the perfusion technique, experimental conditions, and methods used to measure rates of substrate oxidation, ranolazine (10 μM) had no effect on glucose or fatty acid oxidation or glycolysis, whereas CVT-4325 (3 μM) reduced fatty acid oxidation by ~7 fold with a concomitant increase in glucose oxidation. Furthermore, although ranolazine significantly improved recovery of LV function following ischemia/reperfusion, CVT-4325 had no significant protective effect. These results demonstrate that at pharmacologically relevant concentrations, ischemic protection by ranolazine cannot be attributed to inhibition of fatty acid oxidation. Moreover, these data also suggest that direct inhibition of fatty acid oxidation may not be an effective approach for improving functional recovery following ischemia/reperfusion.

Materials and Methods

Materials. Unless otherwise noted, chemicals were obtained from Fisher Scientific (Santa Clara, CA) or Sigma/Aldrich (St. Louis, MO). Essentially fatty acid free bovine serum albumin was obtained from Sigma or Serologicals Proteins Inc. (Kankakee, IL). Radioisotopes were obtained from PerkinElmer Life and Analytical Sciences (Boston, MA), and [1-13C]-labeled substrates were from Cambridge Isotope Laboratories (Andover, MA). Ranolazine and CVT-4325 were obtained from the bioorganic chemistry group at CV Therapeutics (Palo Alto, CA); the structures of these drugs have been reported previously (McCormack et al., 1998; Elzein et al., 2004). Both drugs were prepared as stock solutions of 10 and 3 mM, respectively, in DMSO. The resulting DMSO concentration in the perfusate was <0.1% and was the same for both drugs. In a series of normoxic perfusion experiments, this concentration of DMSO was found to have no adverse effects on function or metabolism.

Animals. Animal experiments were approved either by the Institutional Animal Care and Use Committee at the University of Alabama at Birmingham or Institutional Animal Care and Use Committee of CV Therapeutics and followed the Guide for the Care and Use of Laboratory Animals (National Academy of Sciences, 1996). Male Sprague-Dawley rats (Charles River Laboratories, Inc., Wilmington, MA) weighing 300 to 350 g were used throughout.

Isotopemic Langendorff Heart Perfusion Experiments.

Hearts were perfused at 37°C as described previously in isotopemic Langendorff mode (Wang et al., 2005) with a Krebs-Henseleit solution containing 5 mM glucose, 1.0 mM sodium lactate, 0.1 mM sodium pyruvate, 1.0 mM sodium palmitate, 3% bovine serum albumin, and 100 μM insulin. Cardiac function was continuously recorded via a fluid-filled balloon placed into the LV, connected to a pressure transducer, and LV end diastolic pressure (EDP) was set to 5 mm Hg by adjusting balloon volume at the beginning of the experiments, and the balloon volume was subsequently left unchanged for the remainder of the experiment. To ensure consistency with previous studies using this model, hearts were paced at a constant rate of 320 beats/min throughout the experiment.

In all experiments, hearts were initially perfused in the absence of drug. After 30 min, hearts were randomly assigned to an untreated control group, a ranolazine (10 μM) group, or a CVT-4325 (3 μM) group, and drugs were present for the remainder of the experiments. Hearts were either perfused under aerobic conditions for 60 min or were subjected to low-flow ischemia (LFI; 0.3 ml/min) for 30 min followed by 60 min of reperfusion where flow was restored to achieve a perfusion pressure of 75 mm Hg as described previously (Wang et al., 2005).

In both the aerobic and LFI experiments, hearts were perfused with [U-13C]palmitate, [3-13C]lactate, and [2-13C]pyruvate for the final 30 to 45 min of the protocol, at which time hearts were freeze-clamped and acid-extracted and 13C NMR spectra collected as described previously (Lloyd et al., 2004; Wang et al., 2005). 13C NMR isotopomer analyses of heart extracts as described previously in detail elsewhere (Lloyd et al., 2003; Wang et al., 2005) were performed to determine the relative contribution of substrates to total acetyl-CoA entering the tricarboxylic acid (TCA) cycle.

The concentration of ranolazine used here (i.e., 10 μM) reflects the upper end of the proposed therapeutic concentration range (Belardinelli et al., 2006). The concentration of CVT-4325 was chosen based on the results of preliminary experiments that showed that the maximal inhibition of palmitate oxidation under the conditions of these experiments was achieved at a concentration of ~3 μM (Fraser et al., 2003). Additional studies showed that, at ~3 μM, the predominant pharmacological activity of CVT-4325 in the presence of 1.2 mM palmitate was the inhibition of fatty acid oxidation (IC50 = 0.9 μM) and stimulation of glucose oxidation (IC50 = 5.8 μM) (data not shown). The concentrations of ranolazine and CVT-4325 in the perfusate were assayed at the end of the experiments, and the mean
concentrations were determined to be $12.6 \pm 1.3$ and $2.6 \pm 0.2 \, \mu M$, respectively.

**Working Heart Perfusion Experiments.** Hearts were perfused as described previously in an ejecting (i.e., "working heart") mode (Neely et al., 1967) at 37°C with a Krebs-Henseleit solution containing 5.5 mM glucose, 1.2 mM palmitate, 3% bovine serum albumin, and 100 $\mu M$ insulin and continuously equilibrated with a 95% CO$_2$ and 5% O$_2$ gas mixture. After 10 min of perfusion in Langendorff mode, hearts were switched to working mode, with a constant left atrial preload of 11.5 mm Hg and aortic afterload of 80 mm Hg, and paced at a constant rate of 300 beats/min to ensure consistency with previous studies using this model (Fraser et al., 1999). Aortic systolic and diastolic pressures were measured via a pressure transducer attached to the aortic outflow line and cardiac output and aortic flow were measured using in-line ultrasonic flow probes. Left ventricular minute work (LV work), calculated as (cardiac output) × (left ventricular developed pressure (LVPD)), with LVPD = aortic systolic pressure − preload pressure, was used as an index of mechanical function. LV work was measured continuously. Glucose and fatty acid oxidation rates were measured simultaneously using dual-labeled substrates ($^{14}C$glucose and $^{3}H$[palmitate]) as described previously (Lopaschuk and Barr, 1997). Rates of palmitate and glucose oxidation are expressed as micromoles of substrate metabolized per minute per gram dry weight.

For the aerobic experiments, ranolazine (10 $\mu M$, n = 3) and CVT-4325 (3 $\mu M$, n = 5) were added to the perfusate after 5 min of aerobic perfusion and recirculated for 60 min. Hearts were paced at a constant rate of 300 beats/min throughout the experiment.

In the ischemia/reperfusion experiments, hearts were perfused aerobically for 30 min, followed by 15-min global, zero-flow ischemia induced by clamping off both the preload and afterload lines. After 15 min of global zero-flow ischemia, coronary flow was restored by removing the clamps and reperfusion was continued for 60 min. It has already been shown using a very similar protocol that 10 $\mu M$ ranolazine improved functional recovery on reperfusion (MacInnes et al., 2003); therefore, in these experiments, hearts were either untreated (n = 9) or treated with CVT-4325 (3 $\mu M$, n = 6) added after the first 5 min of preischemic aerobic perfusion. PACing can alter the response to ischemia/reperfusion by potentially exacerbating ischemic injury as well as obscuring the incidence of arrhythmias on reperfusion; therefore, in these ischemia/reperfusion experiments, hearts were not paced.

**Statistics.** All data are presented as means ± S.E.M., with five to six replicates in each group unless stated otherwise. Unpaired Student’s t tests and one-way and repeated measure ANOVA were used where appropriate followed by a Dunnett’s multiple comparison test using Prism 4.0c (GraphPad Software Inc., San Diego CA). Statistically significant differences between groups were defined as $p < 0.05$.

### TABLE 1
Cardiac function data at baseline before addition of drug, 30 min following drug, and at the end of reperfusion in control, ranolazine (10 $\mu M$), and CVT-4325 (3 $\mu M$) groups

<table>
<thead>
<tr>
<th></th>
<th>LVPD</th>
<th>RPP</th>
<th>+dP/dt</th>
<th>−dP/dt</th>
<th>CF</th>
<th>MVO$_2$</th>
<th>RPP/MVO$_2$</th>
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<tr>
<td><strong>Baseline</strong></td>
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<tr>
<td>Control (n = 12)</td>
<td>108 ± 3</td>
<td>34.4 ± 0.9</td>
<td>3.9 ± 0.3</td>
<td>2.2 ± 0.1</td>
<td>9.8 ± 0.3</td>
<td>4.8 ± 0.1</td>
<td>7.4 ± 0.2</td>
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<tr>
<td>Ranolazine (n = 12)</td>
<td>107 ± 5</td>
<td>34.5 ± 1.5</td>
<td>4.0 ± 0.2</td>
<td>2.4 ± 0.1</td>
<td>8.8 ± 0.6</td>
<td>4.1 ± 0.2*</td>
<td>8.5 ± 0.3</td>
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<tr>
<td>CVT-4325 (n = 11)</td>
<td>110 ± 4</td>
<td>35.3 ± 1.3</td>
<td>4.1 ± 0.3</td>
<td>2.5 ± 0.2</td>
<td>8.6 ± 0.5</td>
<td>4.2 ± 0.2*</td>
<td>8.7 ± 0.5*</td>
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<td><strong>Postdrug</strong></td>
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<tr>
<td>Control (n = 12)</td>
<td>110 ± 4</td>
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<td>4.0 ± 0.3</td>
<td>2.3 ± 0.1</td>
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<td>4.7 ± 0.3</td>
<td>7.6 ± 0.4</td>
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<td>Ranolazine (n = 12)</td>
<td>110 ± 4</td>
<td>34.4 ± 1.2</td>
<td>4.3 ± 0.2*</td>
<td>2.5 ± 0.1</td>
<td>8.6 ± 0.5</td>
<td>4.1 ± 0.2</td>
<td>8.7 ± 0.4</td>
</tr>
<tr>
<td>CVT-4325 (n = 11)</td>
<td>148 ± 4*</td>
<td>47.9 ± 1.4*</td>
<td>5.9 ± 0.2*</td>
<td>3.9 ± 0.2*</td>
<td>9.6 ± 0.4*</td>
<td>4.4 ± 0.1</td>
<td>9.8 ± 0.6*</td>
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<td><strong>End reperfusion</strong></td>
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<tr>
<td>Control (n = 6)</td>
<td>61 ± 6</td>
<td>19.7 ± 1.8</td>
<td>2.3 ± 0.3</td>
<td>1.3 ± 0.1</td>
<td>5.2 ± 0.4</td>
<td>2.8 ± 0.2</td>
<td>7.2 ± 0.6</td>
</tr>
<tr>
<td>Ranolazine (n = 6)</td>
<td>80 ± 4*</td>
<td>25.8 ± 1.2*</td>
<td>3.3 ± 0.2*</td>
<td>2.0 ± 0.1*</td>
<td>5.3 ± 0.3</td>
<td>2.9 ± 0.2</td>
<td>9.1 ± 0.7</td>
</tr>
<tr>
<td>CVT-4325 (n = 5)</td>
<td>59 ± 6</td>
<td>18.9 ± 1.8</td>
<td>2.2 ± 0.2</td>
<td>1.5 ± 0.3</td>
<td>3.8 ± 0.5*</td>
<td>2.0 ± 0.2*</td>
<td>9.8 ± 1.1</td>
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* $p < 0.05$ vs. control.
† $p < 0.05$ vs. baseline.

### Results

**Experiments Using Isovolumic Langendorff Heart Preparations.** LV functional data from both the aerobic and LFI experiments are summarized in Table 1. Before the addition of drugs, there was no difference in baseline contractile function among any of the three groups; however, oxygen consumption (MVO$_2$) was significantly lower in the groups subsequently assigned to ranolazine and CVT-4325 compared with the control group, and rate-pressure product (RPP/MVO$_2$) was increased in the group subsequently assigned to CVT-4325. To compare the effects of the two drugs on cardiac function under normoxic perfusion conditions, functional parameters 30 min after the addition of drugs were compared with function in the same hearts at baseline before the addition of drugs. Ranolazine resulted in a small (<10%) but significant increase in +dP/dt but had no effect on any of the other functional parameters including MVO$_2$.

In contrast, CVT-4325 had a significant positive inotropic effect, increasing LVPD and RPP by ~30% and +dP/dt by more than 40%, which was accompanied by a significant increase in coronary flow relative to baseline. However, despite the increase in RPP with CVT-4325, there was no increase in MVO$_2$; consequently, there was a significant increase in efficiency as defined by the ratio of RPP/MVO$_2$.

Thirty minutes after perfusion with ranolazine, there were no differences in function between control and ranolazine groups; however, there was a significant increase in all functional parameters in the CVT-4325 group compared with controls.

The relative contributions of glucose, palmitate, lactate, and pyruvate to total TCA cycle flux from $^{13}C$ NMR glutamate isotope analysis during aerobic perfusion are summarized in Fig. 1. Consistent with previous reports with similar substrate mixtures (Chatham et al., 1999), palmitate contributed ~85% of acetyl-CoA entry into the TCA cycle, lactate ~10%, and the remainder was from glucose and pyruvate. Ranolazine had no effect on the relative contributions of any of the substrates to the TCA cycle; however, CVT-4325 inhibited palmitate oxidation by ~80%, which was accompanied by a more than 4-fold increase in lactate and pyruvate oxidation and approximately 9-fold increase in glucose oxidation.

The effects of ranolazine and CVT-4325 on LV EDP during
LFI are summarized in Fig. 2. Ranolazine treatment appeared to shift the EDP curve to right (Fig. 2A); however, due to the large variance in the data, there was no difference between groups when analyzed via repeated measures ANOVA. Nevertheless, the time to onset of contracture during LFI, defined as the time EDP reached $\geq 10$ mm Hg, was significantly delayed in the ranolazine group (Fig. 2B), and the EDP averaged over the duration of LFI was significantly lower with ranolazine treatment (Fig. 2C).

The time course of recovery of RPP during reperfusion is summarized in Fig. 3. ANOVA indicated a significant drug effect, and post hoc test indicated significant differences between ranolazine and other two groups at individual time points between 2 and 10 min (repeated measures ANOVA, $p < 0.05$). Values are the mean $\pm$ S.E.M. of five to six experiments in each group.

LV function at the end of reperfusion is summarized in Fig. 4 and Table 1. After 60 min of reperfusion, ranolazine treatment improved functional recovery compared with the control group; in contrast, despite the marked reduction in fatty acid oxidation, CVT-4325 did not improve recovery of LV function postischemia; indeed, relative to preischemic values, recovery of LV function was significantly lower than that observed in the con-
During reperfusion, oxygen consumption in the CVT-4325 group was significantly lower; however, in contrast to normoxic perfusion, efficiency (RPP/MVO₂) was not significantly different between groups. At the end of reperfusion, LV EDP was significantly lower in the ranolazine group compared with the control group (20 ± 5 mm Hg; p < 0.05 versus control). CVT-4325 had no effect on end reperfusion EDP (33 ± 5 mm Hg; p > 0.05 versus control).

Substrate oxidation in the three groups during reperfusion is summarized in Fig. 5. Similar to the results of experiments in normoxic conditions, ranolazine had no effect on the relative utilization of palmitate, lactate, glucose, or pyruvate, whereas CVT-4325 significantly decreased palmitate utilization with a concomitant increase in lactate, glucose, and pyruvate oxidation. However, compared with normoxic perfusion, the inhibition of fatty acid oxidation by CVT-4325 was significantly attenuated.

**Working Heart Experiments.** To ensure that the results above were not specific to the isovolumic perfused heart preparation, fatty acid and carbohydrate oxidation rates were also determined in isolated perfused working hearts (Fig. 6). Similar to the results of experiments using the isovolumic Langendorff heart preparation, ranolazine had no effect on the rates of either glucose or fatty acid oxidation; however, CVT-4325 decreased fatty acid oxidation by ∼4- to 5-fold, with a concomitant increase in glucose oxidation.

Previously, 10 µM ranolazine has been shown to significantly improve functional recovery following zero-flow ischemia and reperfusion in a working perfused heart model (MacInnes et al., 2003); however, the effect of CVT-4325 on the response of LV function to ischemia in this model has not been reported previously. Therefore, to determine whether the lack of protection seen with CVT-4325 in response to LFI in the isovolumic perfused heart was specific to that model, we examined the response of the working heart to zero-flow ischemia and reperfusion with and without CVT-4325. Similar to the isovolumic perfused heart experiments preischemic cardiac work was increased in the CVT-4325 group compared with controls (9.2 ± 0.2 versus 7.9 ± 0.4 mm Hg l/min; p < 0.025). Following ischemia/reperfusion, cardiac work was ∼40% of preischemic levels in both control and CVT-4325 groups; however, there were no differences in cardiac function between these two groups (Fig. 7).

**Discussion**

In light of the controversies regarding the effect of ranolazine on cardiac metabolism and the proposed cardioprotective effects of inhibiting fatty acid oxidation, we compared,
for the first time, the effects of ranolazine with a new potent fatty acid oxidation inhibitor, CVT-4325, on fatty acid and carbohydrate oxidation in the heart. The results demonstrate that at pharmacologically relevant concentrations, ranolazine had no effect on fatty acid or carbohydrate oxidation and that this was independent of the perfusion technique, the method used to measure substrate oxidation, or the perfusion protocol. The lack of effect of ranolazine was in contrast to CVT-4325, which markedly reduced fatty acid oxidation with a concomitant increase in carbohydrate oxidation in both the isovolumic and working heart preparations. Moreover, despite having no effect on substrate utilization, ranolazine significantly improved the recovery of LV function following ischemia, whereas CVT-4325 did not improve functional recovery following either LFI or zero-flow ischemia. This side-by-side comparison of ranolazine with CVT-4325 provides compelling evidence that the mechanism underlying the protection seen with ranolazine cannot be attributed to alterations in substrate utilization either before ischemia or during reperfusion. Furthermore, the fact that CVT-4325 did not improve functional recovery following either LFI or zero-flow ischemia suggests that direct inhibition of fatty acid oxidation may not be an effective approach for improving functional recovery following ischemia/reperfusion.

Ranolazine has been shown to be protective against myocardial ischemic injury in a number of experimental settings (Clarke et al., 1996; McCormack et al., 1996; MacInnes et al., 2003) and has also been found to be efficacious as an antian-.

Fig. 6. Effect of RAN (10 μM) and CVT-4325 (3 μM) on glucose and palmitate oxidation under aerobic conditions in working heart perfusions. Values are the mean ± S.E.M. of five to six experiments in each group. *p < 0.05 versus control.

Fig. 7. Cardiac function after 15-min no-flow ischemia and 60-min reperfusion in control and CVT-4325 (3 μM) groups.
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One frequently cited explanation for the beneficial effect of increasing glucose oxidation relative to fatty acid oxidation is that it improves efficiency because the amount of ATP produced per unit oxygen consumed is ~12% greater when glucose is oxidized compared with palmitate (Stanley et al., 1997a). Interestingly, we found that CVT-4325 did improve efficiency (Table 1); however, the magnitude of this change was greater than can be attributed to the decrease in palmitate oxidation. Furthermore, despite this increase in efficiency, functional recovery was not improved. However, it should be noted that this increase in efficiency was associated with a significant increase in RPP, which could adversely affect the response to ischemia. The mechanisms underlying the increase in contractility and efficiency associated with CVT-4325 are unknown at this time and warrant further study.

A potential limitation associated the use of any pharmacological inhibitors is their specificity. Therefore, CVT-4325 was tested for potential pharmacological activity (using the MDS-Pharma SpectrumScreen; MDS Pharma Services, King of Prussia, PA) at 169 targets that included G-protein-coupled receptors (e.g., β-adrenergic receptors), nuclear hormone receptors (e.g., estrogen receptor-α), and transporters (e.g., serotonin). CVT-4325 at 10 μM inhibited (≥70%) serotonin, histamine, L-type calcium channel, and serotonin transporter (J. A. Zabolci, unpublished data on file at CV Therapeutics, Inc.). Thus, at the concentration used in the present study (3 μM), the predominant pharmacological activity of CVT-4325 in the presence of 1.2 mM palmitate was the inhibition of fatty acid oxidation (IC_{50} = 0.9 μM) and stimulation of glucose oxidation (IC_{50} = 5.8 μM). Nevertheless, it is conceivable that the lack of myocardial protection associated with CVT-4325 may be due to potentially adverse effects associated with targets independent of fatty acid oxidation inhibition.

It should also be noted that we compared only single concentrations of ranolazine and CVT-4325 rather than using multiple overlapping concentrations, which would have provided a more comprehensive comparison of these agents. However, the primary purpose of this study was to examine the effects of ranolazine at a therapeutically relevant concentration on cardiac metabolism and the response to ischemia and to compare this directly with an inhibitor of fatty acid oxidation. At 300 μM, MacInnes et al. (2003) reported that ranolazine inhibited β-oxidation in cardiomyocytes by ~30%, demonstrating the potential for ranolazine to inhibit fatty acid oxidation at high concentrations. However, because 10 μM reflects the upper end of the proposed therapeutic concentration range for ranolazine (Belardinelli et al., 2006), it is highly unlikely that its effect on fatty acid oxidation is therapeutically relevant. CVT-4325 is clearly a potent inhibitor of fatty acid oxidation, reducing palmitate oxidation by 80% at a concentration of only 3 μM; consequently, we cannot entirely rule out the possibility that at lower concentrations with more modest inhibition of fatty acid oxidation CVT-4325 may have demonstrated some beneficial effects.

There were some differences in protocols between the isovolumic Langendorff and working heart experiments. For example, in the isovolumic studies, physiologically relevant concentrations of lactate and pyruvate were used in addition...
to glucose, whereas in the working heart studies glucose was the only carbohydrate source. Furthermore, in the isovolumic studies, hearts were paced at 320 beats/min in both normoxic and ischemia/reperfusion experiments, whereas in the working heart experiments hearts were paced at 300 beats/min in the normoxic experiments and unpaced in the ischemia/reperfusion experiments. Some of these differences such as the pacing rate would not be expected to affect the metabolic measurements or the response to ischemia; however, substrate availability and pacing during ischemia/reperfusion could potentially affect both. Nevertheless, despite these differences in perfusion conditions, the effects of ranolazine and CVT-4325 were remarkably consistent in these two different experimental models.

In conclusion, we have shown that regardless of the perfusion conditions, ranolazine had no effect on glucose or fatty acid oxidation. Nevertheless, in the isovolumic perfused heart model, it attenuated the development of ischemic contracture and improved recovery of function following ischemia/reperfusion. In contrast, in both the isovolumic and working heart models, CVT-4325 markedly reduced fatty acid oxidation with a concomitant increase in glucose oxidation but did not improve functional recovery. These results demonstrate that at pharmacologically relevant concentrations, ischemic protection associated with ranolazine is mediated by mechanisms other than inhibition of fatty acid oxidation and conversely that significant inhibition of fatty acid oxidation with CVT-4325 is not associated with cardio-protection.

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References

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